

TECHNIQUES FOR MEASURING VENTILATION RATE THROUGH NATURALLY VENTILATED BUILDINGS

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ABSTRACT: The objective of this work was to develop both an accurate reference measurement technique to determine ventilation rates through naturally ventilated buildings and a practical direct measuring principle for online and continuous field measurements of ventilation rates through naturally ventilated sections. Using a tracer-gas decay technique to analyse 444 laboratory experiments in a ventilated room, with a reference technique for scientific and calibration purposes, revealed a 35% inaccuracy. Aside from the assumption of perfectly mixing, a zonal modelling approach was used for post-processing of tracer-gas data and allowed a 14% inaccuracy, even at low ventilation rates. To develop a measuring sensor for continuous use on farms with natural ventilation systems, two measuring principles were tested in laboratory conditions: 1) Heat dissipation from the heat source at 17 different ventilation rates of a test room in comparison with an accurate ventilation reference measurement. This technique provided 15% inaccuracy as an average for all laboratory experiments. 2) Transit time sonic anemometers were developed for a large-scale section by using 16 acoustical lines. They were tested in a chimney with a large diameter ($\Phi = 0.80$ m) and a length of 1.1 m. In total, 980 experiments were performed in combination with a reference technique and resulted in a 9% inaccuracy, even at disturbed flow conditions.

Keywords: measuring, ventilation rate, naturally ventilated buildings

INTRODUCTION: Almost all techniques to measure ventilation rates through naturally ventilated buildings suffer from lack of a standard and reliable reference technique to compare their accuracies. The tracer gas method is one of the most popular methods used in ventilation rate determinations in naturally ventilated buildings. The method is based on conservation of mass of an inert tracer gas injected into a building section (von Pettenkofer, 1858). The use of an artificial tracer gas, such as SF₆, is much preferred over the heat balance or CO₂ method (Phillips, et al., 2001). The tracer gas decay technique was chosen for further evaluation as a reference measurement method, as it is already widely used in the research environment, and is also used in certain practical situations. This technique provides information about global ventilation rates throughout the livestock house. While applying the tracer gas method, airflow characteristics of the ventilated space should also be considered. Therefore, this technique was further improved by incorporating it into a zonal modelling approach where distribution of tracers in space was considered.

Firstly, for field applications, an innovative measurement strategy that relies on temperature tracing of the flow field through inlet openings was largely suggested compared to the hot wire anemometer (Eren Ozcan et al., 2005). Basically, a heat source was introduced at the air opening and the ventilation rate was estimated from the rate of cooling. Secondly, a technique called “transit-time sonic anemometer” was examined and optimised at a standard test rig with a comparable scale of usual air inlet. Low ventilation rates and variable flow regimes typical to natural ventilation were reconstructed. These last two techniques were evaluated as practical tools for use in field measurements of ventilation rates through naturally ventilated buildings in the future.

1. MATERIAL AND METHODS: This study initially aims to test the tracer gas technique in laboratory test installations, which is often used as a reference method (Jiang & Chen, 2003). The tracer decay method was chosen. Drawbacks, such as fluctuations in ventilation rates and non-uniform injection of tracers at the air inlet, are minimal in well-controlled laboratory test installations.

1.1. Tracer-decay method: The method is based on the mass balance equation of the tracer gas in the air (Equation 1)

$$vol \cdot \frac{dC_i}{dt} + V \cdot C(T) = i \quad (1)$$

where vol is the total volume of the ventilated space in m^3 ; C is the concentration of tracer gas in kg/m^3 at time t ; V is the ventilation rate in m^3/s and i is the injection rate of tracer gas in kg/s inside the building volume.

In reality, gradients exist and, depending on sampling position, overall ventilation rate calculations will vary. Therefore, the accuracy of the tracer decay method was tested against a standard measuring technique (orifices) where the amount of ventilation is known with an accuracy of $6 m^3/h$.

1.1.1. Laboratory test installation: The laboratory test room was a mechanically ventilated room ($3.0 \times 2.0 \times 1.5 m$). It had a slot inlet in the left sidewall just beneath the ceiling, which had a $1.24 m$ width and a $0.036 m$ height, and was positioned $1.55 m$ above the floor. An asymmetrically positioned, circular air outlet with a $0.16 m$ diameter (Φ) was located $0.21 m$ above the floor at a $0.31 m$ distance from the front wall. An enveloping chamber ($4.0 \times 2.5 \times 3 m$) was built around the test room to reduce disturbing effects. Detailed description of the test installation (Figure 1) can be found on Berckmans et al. (1993) and Janssens et al. (2004).

A mechanical ventilation system composed of a centrifugal fan and a movable cone to regulate a computer controller step motor enabled accurate measurement and control of the ventilation rate in the range of $70 - 420 m^3/h$ ($7.6 - 46.6$ air changes per hour, ACH), with an accuracy of $\pm 6 m^3/h$. The reference technique to measure the ventilation rate is an orifice built according to the standard DIN 1952 (1982). A heat exchanger provided in the air supply duct regulated the temperature of the inflowing air from 10 to $30 ^\circ C$. The heat production of different heating elements can be controlled from 0 up to $120 J/s$ with an accuracy of $1 J/s$. To measure the three dimensional (3-D) spatio-temporal gas concentration distributions in the test chamber, 36 air sampling tubes are located in a 3-D measuring grid. The gas injection rate was controlled at a rate of $1.3 \times 10^{-4} kg CO_2/s$. When all the positions reached a steady tracer gas concentration, injection of CO_2 was stopped and decay rates from each position were recorded as a measure of ventilation rate at a certain point i in space, as well as the relative measurement error E_i in %, which represents the margin of inaccuracy by choosing different sampling positions.

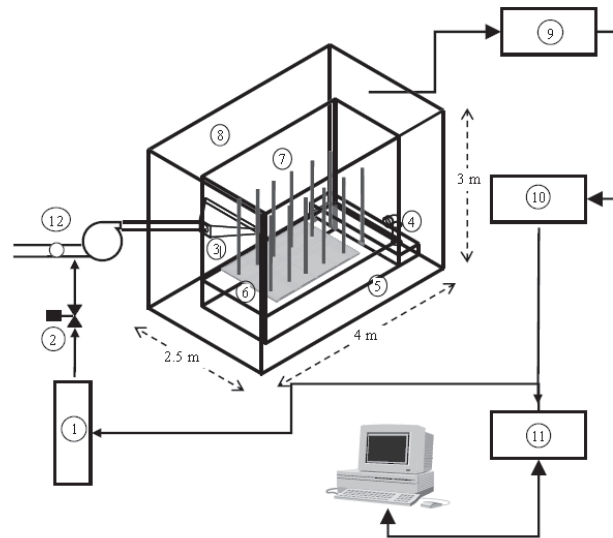


Figure 1. Laboratory test chamber with sampling system to measure spatial gas concentration distributions: (1) pressurised CO₂ gas bottle; (2) gas flow rate controller; (3) air inlet; (4) air outlet; (5) shallow water reservoir (6) aluminium conductor heat sink; (7) 3D measurement grid consisting of 36 sampling tubes; (8) envelope chamber or buffer zone; (9) multipoint sampler consisting of pc-controlled solenoid valves; (10) gas analyser; (11) data logging system; (12) orifice.

Tracer gas data were collected for six different ventilation rates (9, 13, 18, 22, 27 and 33 ACH) at the 36 positions in the sample grid and at the outlet. Each experiment with a certain ventilation rate had two repetitions. The sampling of the tracer gas at a specific sampling position lasted for one hour and twenty minutes under steady conditions. In total, 444 datasets (37 positions x 6 ACH, and 2 repetitions) were collected, which corresponds with a total experimental time of 493 hours. The sampling rate was 3.3 s.

1.2. Ventilation rate measurement based on heat dissipation: Temperature readings were used to construct an innovative prediction method for total ventilation rate estimations through naturally ventilated openings. Heat dissipated at the air inlet was used to track air flow through an inlet section. Since there is no accurate reference technique yet defined for natural ventilation in the field, a mechanically ventilated test rig (Eren Ozcan, 2011) with a standard ventilation rate measuring unit was used to test the working principle of the temperature-based method. Steady-state conditions with and without external disturbance were created at two heating levels (30 W and 50 W) in combination with 17 different ventilation rates (from 100 to 1500 m³/h) and four different vertical disturbance levels to provide information at different flow conditions.

1.3. Ventilation rate measurement based on acoustics: Acoustical sensors, which determine the ventilation rate through a ventilation opening ($\Phi = 0.58$ m) with a non-uniform flow pattern at low average air speeds (0 – 0.5 m/s), as in naturally ventilated buildings, were analysed. A prototype sensor was developed with 32 (2 x 16) acoustical sensors embedded into a tube with a 0.58 m diameter and 1.10 m in length. The sensors were Quantelec type, ultrasonic ceramic transducers that work with a frequency of 40

kHz. Detailed descriptions of the structure of the prototype sensor and test installation are available at Eren Ozcan (2011).

2. RESULTS AND DISCUSSION:

2.1. Tracer-decay method: The accuracy of the tracer gas technique tested highly depends on injection and sampling positions. Measurement errors up to 86% of the actual ventilation rate were observed using the decay method due to non-perfect mixing. The overall best place for tracer gas sampling was the outlet position with less than 10% measurement errors. However, in most naturally ventilated buildings the position of the outlet is often not known.

The results of the measurement errors on the ventilation rate compared with an accurate reference method (a standard orifice) are shown in Table 1.

Table 1. Comparison of relative errors in ventilation rate calculations with perfect mixing assumption and zonal model approach at different ventilation rates.

Air change rate (l/h)	Relative error (%)						
	9	13	18	22	27	33	Average
Single zone - outlet	5.1	2.3	6.0	3.9	15.3	13.1	7.6
Single zone – average	26.1	30.8	30.9	22.3	29.3	68.6	34.7
Zonal Model	19.5	14.7	20.9	1.5	16.0	8.8	13.6

The zonal modelling approach using multi-point sampling and analysis enabled the reduction of the average inaccuracy of tracer gas measurements from 35 % to 14% of the reference reading from orifices.

2.2. Heat dissipation: A more practical method for continuous use on farms with natural ventilation was tested based on velocity mapping at air inlets by the help of a heat source and temperature sensors. The physical relation between temperature difference (heat source and surrounding air) and ventilation rate was presented with validation against experimental results. Ventilation rates through openings showed an inaccuracy of 15% compared to orifice measurements, even in non-uniform flow conditions created by an external fan above the inlet opening.

2.3. Acoustics: Single and multiple acoustical measuring lines were tested at uniform and non-uniform flow patterns in the ventilation opening. From the experiments, it was concluded that 16 measuring lines gave accurate results with 9% inaccuracy at a range of 200 to 1000 m³/h in a large ($\Phi = 0.58$ m) chimney, even at non-uniform flow conditions (Table 2).

Table 2. Overview of the results with one and 16 measuring lines, in both directions, with and without a disturbance at the inlet at a range of 200 to 1000 m³/h.

Method	n	Standard Error (m ³ /h)	Measurement Error (%)
One line, no disturbance	80	46	12
One line, with disturbance	80	85	24
16 lines, no disturbance	30	12	7
16 lines, with disturbance	40	34	9

CONCLUSION: When using tracer gases to determine ventilation rates through naturally ventilated buildings, large variations in gas concentrations were observed inside the ventilated airspace due to non-perfect mixing (86%). Using a number of points distributed uniformly in space and calculating the amount of fresh air at each position, it was possible to reduce inaccuracy of tracer gas measurements from 35 % to 14%, on average. Therefore, tracer gas measurements can be improved by using more sampling points to assess ventilation rates through naturally ventilated buildings. The number and the position of these sampling points can be determined with a preliminary study. This method was useful as a reference method for research and calibration purposes.

As a tentative step to develop a measuring sensor for continuous use on farms with natural ventilation systems, the results of the heat dissipation study demonstrate that the temperature can be used as a means to determine ventilation rates with a 15% inaccuracy. However, robustness of the system still needs improvement through testing at various conditions and by optimising the current design.

For practical applications, the transit time acoustical measuring method offers a unique opportunity for ventilation rate measurements through naturally ventilated buildings' exhausts. Both the applicability and the 9% accuracy (disturbed flow conditions) of the transit time sonic anemometer is acceptable for field applications, which is a promising technique for further development in real-scale buildings.

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